Using Virtual Reality to Explore Older Adults' Preferences for Green Streets: Design Guidelines

Utilizzo della Realtà Virtuale per esplorare le preferenze degli anziani per le strade verdi: linee guida di progettazione

*Con l'invecchiamento della popolazione, la progettazione degli spazi pubblici deve rispondere ai bisogni degli anziani per prevenire l'esclusione sociale causata da barriere architettoniche. Tuttavia, l'ambiente costruito esistente rimane ancora insufficientemente accessibile, in particolare nella progettazione delle "*green streets*", che integrano modalità di mobilità attiva come biciclette e monopattini insieme alla vegetazione. La progettazione di questi spazi spesso trascura le esigenze dei pedoni anziani. Per creare spazi pubblici realmente inclusivi, è essenziale promuovere il coinvolgimento diretto degli anziani nei processi decisionali locali relativi alla loro progettazione.*
L'obiettivo principale della ricerca è studiare gli effetti della progettazione delle green streets *urbane sulla mobilità, sull'integrazione sociale e sull'invecchiamento. Inoltre, intendiamo integrare metodologie all'avanguardia, come le tecnologie di realtà virtuale (VR) e le misurazioni fisiologiche, per simulare sperimentalmente specifici ambienti stradali e valutare le percezioni naturali degli anziani rispetto a tali spazi.*
Il progetto si sviluppa in tre fasi. La fase 1 si concentra sull'analisi del concetto di green streets *e della loro integrazione nei piani verdi della città di Lisbona da una prospettiva architettonica. Attraverso osservazioni e investigazioni sceintifiche, la fase 2 esamina la percezione e l'uso delle* green streets *da parte degli anziani. Nella fase 3, testiamo l'impatto di questi ambienti sulla "camminabilità", sull'integrazione sociale e sui modelli di invecchiamento utilizzando la VR. L'utilizzo di un ambiente VR ci consente di simulare contesti "verdi" e "non verdi" e di testare gli effetti causali di caratteristiche specifiche della strada sia su esiti soggettivi sia su esiti oggettivi.*
Questo articolo descrive il sistema tecnologico impiegato per l'esperimento in VR, inclusi la progettazione dell'ambiente immersivo e i protocolli per la raccolta dei dati biometrici. È stato adottata una progettazione sperimentale between-subjects *con quattro parametri. I partecipanti vivono una delle quattro configurazioni stradali, in cui manipoliamo le caratteristiche delle* green streets *secondo un progetto fattoriale 2 (presenza o assenza di vegetazione) x 2 (pista ciclabile congiunta o separata). Abbiamo seguito approcci all'avanguardia per progettare l'ambiente VR adatto agli anziani e per raccogliere dati oggettivi. Le misure oggettive includono segnali biometrici, come la variabilità della frequenza cardiaca e il tracciamento dello sguardo e delle fissazioni, che possono essere correlati agli stati di attivazione e attenzione negli anziani. Le percezioni soggettive vengono valutate tramite un questionario. La definizione delle quattro simulazioni stradali in VR considera diversi aspetti chiave, qui discussi, come la presenza e il realismo della luce naturale, della vegetazione, del suono, delle persone virtuali (agenti), degli oggetti e degli edifici. Inoltre, viene effettuata un'analisi critica delle strategie progettuali, attingendo alla letteratura esistente e agli obiettivi specifici del nostro studio.*

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Introduction

As urban populations age, public space design must address older adults' needs to prevent social exclusion caused by built environment misfits. Nonetheless, the existing built environment remains insufficiently accessible, particularly in the design of green streets, which integrate active mobility modes, such as bikes and scooters, alongside vegetation (Dill *et al.*, 2010). The design of these spaces often overlooks the needs of older pedestrians. Empowering older individuals in local decision-making regarding their design is essential to achieve truly inclusive public spaces.

Under the scope of an ongoing research project – "GreenCity4aging: the effects of urban green streets on mobility, social integration, and ageism against older people" (https://greencity4aging-iscte.hub.arcgis.com/) – our main goal is to research the effects of the urban green streets design on mobility, social integration, and ageism against older people. Moreover, we are integrating state-of-the-art methodologies, such as virtual reality (VR) technologies and physiological measurements, to support our experimental approach of simulating specific street environments and assessing older people's perceptions of these spaces.

This paper aims to report and discuss our experimental user study design, including the setup of an immersive virtual environment (IVE), its technological apparatus, and the protocols for collecting biometric user data.

Virtual reality simulations have been used for some years now to perform studies on the preferences of users related to the built environment due to their ability to simulate reality in a quasi-real way(Birenboim *et al.*, 2019). Regarding older adults, diverse research has been done using VR-base experiments. One trend is the use of VR Applications to aid older adults (e.g. for care, see Wilding *et al.*, 2024). Another is to use VR to simulate reality for user studies with older adults (e.g. to assess the fear of falling, see) (Leite *et al.*, 2019). According to Ijaz *et al.*(2022), user studies consist mainly of designed bespoke experiences such as the one presented in this study. Although those studies are frequent, Ijaz *et al.* (2022) mention that VR systems still pose various challenges for older users, such as cybersickness, discomfort, and heavy HMDs. Also Wilding *et al.*(2024) mention infrastructure conflicts and time constraints as barriers, while the enthusiasm of caregivers and older adults was considered a facilitator.

This paper is organised into six sections. Following the Introduction, which outlines the context and objectives of the study, we provide a brief overview of the GreenCity4Aging research project, within which this work was conducted. Section three details the design of the IVE, the experimental conditions, and the hypotheses formulated. Section four focuses on the visual and auditory modelling of the IVE, with references to relevant literature. In section five, we present the selected hardware for virtual reality and biometric sensing, and we also discuss these choices, considering existing research. Finally, section six offers a conclusion and outlines directions for future work.

Greencity4Aging context

With an ageing population, notably living in urban settings, and increasing climate change challenges, cities must adapt urban structures to promote healthy and active lifestyles for older adults. The concept of "age-friendly cities" (WHO 2007) emphasises inclusive urban planning. Recent trends focus on "green streets," which integrate vegetation and active mobility (walking, cycling) to enhance sustainability and social integration. Studies show the benefits of green streets for the general population, but their impact on older adults is less understood, especially regarding walking safety and potential exposure to ageism. One key issue that remains unresolved is how to design streets that effectively accommodate both walking and cycling. Some studies recommend particular attention to the layout of these lanes, suggesting that separating cycling and walking paths, rather than combining them, can help reduce feelings of insecurity among older adults (*Shared paths – the issues* 2015).

The focus of the GreenCity4Aging project is on the perceptions, emotions, and behaviours of older people regarding different urban street designs. This multidisciplinary project explores how green street designs affect older adults' mobility, social integration, and experiences of ageism. It also investigates whether urban environments can influence societal attitudes toward ageing, offering a novel test of stereotype-embodiment theory.

The project is developed in three phases. In phase 1 we focused on analysing the concept of green streets and their integration into national and municipal strategies in Portugal and Lisbon, from an architectural perspective(Samora-Arvela *et al.*, 2025). We also conducted interviews with stakeholders. During this phase, neighbourhoods to be included in the observational and survey studies of Phases 2 and 3 were also identified. Through observations and surveys, phase 2 examined older people's perceptions of walkability, social integration, and experiences of ageism and uses of green streets. The collected data was mapped using a Geographic Information System (GIS) to create a spatial representation of preferences and perceptions related to neighbourhood street environments. In phase 3, we aim to examine the causal impact of different environmental settings on perceived walkability, social integration, and ageism using an experimental approach. By leveraging VR technology, we can simulate 'green' and 'non-green' urban environments to isolate and test the effects of specific street features, such as vegetation, bike lanes, and pedestrian paths. The development of this phase is the core topic of this paper and will be detailed in the next sections.

The IVE experimental design

In phase 3 we test the core idea of the project using an experimental design. A between-subjects experimental design with four conditions is used. Participants experience one of four street profiles (A, B, C, or D), where we manipulate green street characteristics based on a 2 (presence or absence of vegetation) x 2 (separated or joined cycle lane) factorial design. To assess participants' perceptions and interactions within these virtual streets capes, we use state-of-the-art methods, combining both objective and subjective measures. We hypothesise an interaction effect of the street features, with participants in the "vegetation and separate lanes" (profile A) showing more favourable outcomes compared to the other profiles (B, C, and D).

We follow state-of-the-art approaches to design the IVE for older adults and collect objective data. Objective measures include biometric signals, such as gaze and fixation (using an eye-tracking device) and heartbeat rate HBR (using an HBR sensor), that can be correlated with arousal and attention states in older adults. Subjective perceptions are assessed through a questionnaire measuring walkability perceptions, social integration, and perceived ageism.

For the tests, participants are randomly assigned to one of the four experimental conditions and tested individually using the IVE. Participants enter one of the virtual urban street environments and are instructed to walk straight forward toward a destination (the crossing at the end of the street). During the experiments, participants will be seated and equipped with an Oculus Meta Quest Pro HMD (to experience the IVE and record gaze data) and an HBR bracelet (to record HBR data), as described in the following sections. While using the HMD, participants will be asked to think aloud. After completing each IVE, they will answer a set of questionnaires.

The immersive environment modelling

The definition of our four street simulations in VR includes several key aspects discussed in this section, such as realism, buildings and objects, vegetation, lighting (and shadows), virtual people (agents) and sound. Additionally, we critically examine design strategies, drawing on existing literature and the specific aims of our study (Strojny *et al.*, 2020, Abeele *et al.*, 2021, Campo-Prieto *et al.*, 2021, del Aguila *et al.*, 2021).

We aimed to model an entire street approximately 500 m long, which resembled a street in Lisbon. The 500 m would enable a navigation of circa 10 minutes at a constant speed of 0,9 m/s (Fitzpatrick *et al.*, 2006). The buildings were initially modelled with Revit software, and later, the IVE was developed using the Unity game engine. Unity, along with Unreal software, is increasingly used to deliver simulations for architecture, urban planning and user studies (Indraprastha and Shinozaki, 2013). The modelled urban environment includes static and dynamic objects, real-time rendering and spatial audio elements to simulate realistic outdoor street scenarios.

The balance between the level of realism of an IVE has been discussed by several authors. Taking into consideration that we aim to simulate a real street where all elements are relevant (i.e. trees, different sidewalk pavement, light, shadows, etc.), we opted for a realistic modelling approach while also avoiding over stimulation by not using stimuli that are non-task critical (Abeele *et al.*, 2021). We took special care to use real but contrasting ratios and illumination that would make the scenario understandable even for people with some vision problems, as it might happen with older adults. To enhance user experience, we took care of aspects of presence, namely by providing nature-oriented elements such as trees, providing scenic value with all the visible horizon populated with a diverse and congruent street environment that is perceived as a whole (Abeele *et al.*, 2021). Although the modelled streets do not exist in reality, we paid special attention to modelling them in such a way that they look familiar to the participants.

The built street elements, such as sidewalks, bike and car lanes, and buildings, were modelled using a combination of synthetically modelled elements and photorealistic assets (e.g., photos) collected in selected locations in Lisbon by the authors, to enhance visual realism. The geometry of buildings, as well as the materials used, mimic those found in similar streets in Lisbon. Special attention was given to the traditional pavement in limestone cobblestones that is present in most Lisbon streets (Fig. 01). A pothole was included in the sidewalk to observe how the participants would go around it. Such potholes are very common in cobblestone streets.

Vegetation is one of the aspects studied when addressing green streets. Besides the environmental and mental benefits trees bring to cities, on sunny days, trees also create shadows and protect older adults from intense sun exposure. Replicating such a shadow effect was relevant for our study and therefore, trees and light conditions were designed to create this environment (Figg. 01-02).

Bikes also represent an important part of the green streets' concept. Although on the one hand they promote ecological environmental benefits, on the other hand, they also represent a difficult challenge for older adults due to their speed and proximity. Including bikes in the model was therefore crucial. We opted to include a regular-speed bike passing by the participant and a second bike passing faster (Fig. 02).

Based on our real-site observations taken during phase 2, we calculated the average number, age, and ethnicity of pedestrians to represent them in the IVE accurately. While including virtual agents representing humans is essential to provide a human scale to the IVE, existing literature warns that agents can potentially distract participants during experiments. To mitigate this, we positioned such agents at a sufficient distance so that their presence was noticeable, but their facial expressions were not discernible (del Aguila *et al.*, 2021).

Diverse authors have discussed the role of soundscape design to enhance the sense of presence and realism in an IVE (Serafin and Serafin, 2004, Eloy *et al.*, 2023). Sound has a profound influence on our perception of the environment (Kınayoğlu, 2009). According to these authors, using sound in an IVE can help create a sense of place, and combined with the visual

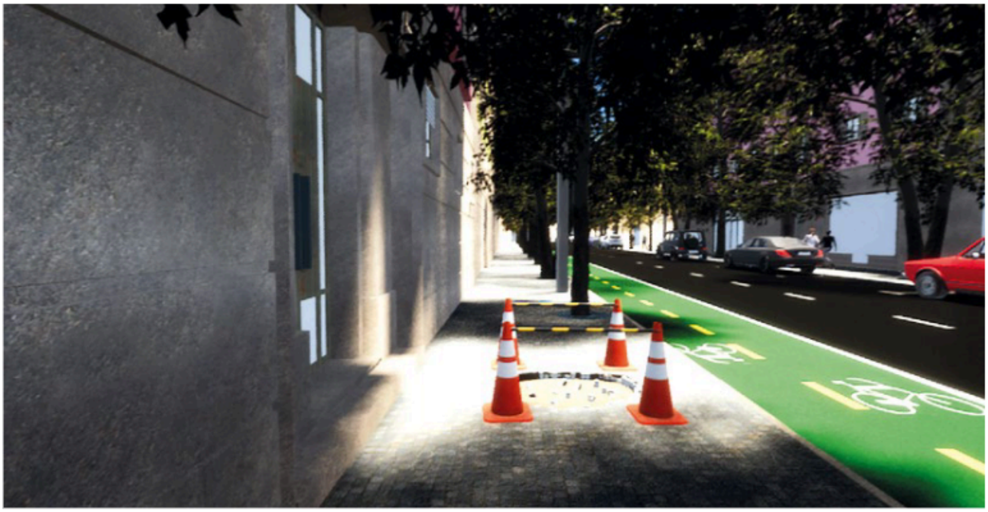

Fig.01 Part of the street in condition A (with vegetation and with separate lanes), showing the critical eventwith the pothole.

characteristics, it is relevant to increase the similarity to a real environment. Additionally, using more sensory experiences as eyesight deteriorates becomes more important (Abeele *et al.*, 2021). As we did for the physical aspects of the street, in this study we aim to use the soundscape of the real environment as closely as possible, but avoiding aesthetically unpleasant sounds, such as hard noises of close-by fast cars, ambulances, and other sounds that could distract the participant (Kınayoğlu, 2009). Pleasant sounds like birdsong were excluded too to isolate the effects of vegetation, as some studies suggest such sounds can influence emotional responses (Ratcliffe *et al.*, 2013). With this in mind, we recorded ambient sounds from one of the Lisbon streets used as a reference for developing the virtual scenarios, specifically capturing audio during nighttime hours, when the soundscape is generally more consistent and freer from disruptive noise.

The hardware and biometric sensing data

As mentioned, the study aims to collect objective measures such as gaze behaviour and heartbeat rate (HBR).

Due to the complex logistics of involving older adults as participants in this study, our experimental apparatus must be movable so that we can conduct the experiments in various venues throughout the city where senior housing facilities are located. Regarding the use of VR hardware, we have followed good practices reported in previous studies with older adults (Brown 2019, Ijaz *et al.*, 2022).

We are interested in verifying the biometric signals of participants when they experience elements such as being close to the bike lane, the trees (canopy), the sidewalk, the pothole, and the bikes passing by. The different configurations of the modelled streets allow us to study participants' reactions to various street designs. For example, when encountering obstacles such as potholes, older participants may choose to use the bike lanes, even at the risk of being hit by a bicycle.

Three critical events were introduced in the scene: i) the pothole, ii) the regular speed bike passing by, iii) the fast bike passing by. The appearance of the two bikes was synchronised with each participant's movement so that the bikes would appear exactly at the same position in the streets independently of how fast the participants arrived at that place.

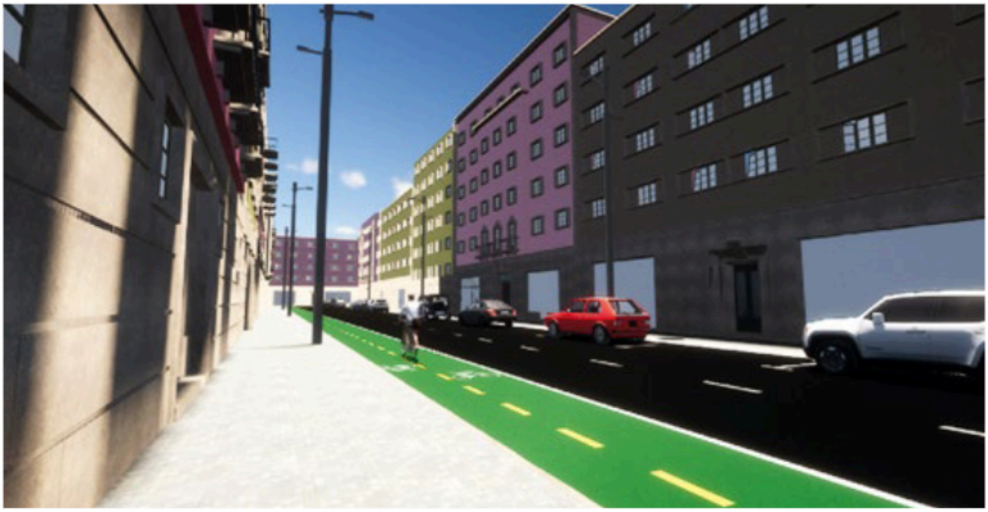

Fig.02 Part of the street in condition B (without vegetation and with separate lanes), showing the critical event where the fast bike passes.

Regarding the duration of the immersive experience, we identified several practices which show that the duration will vary from one study to another, with no standard sufficient exposure, except for the fact that it should last at least several tens of seconds (Birenboim *et al.*, 2019). Indeed, these authors consider a limitation of a maximum of 10 minutes. Initially, we planned that each IVE experiment would last for 10 minutes, which is the time that, on average, an older person takes to walk circa 500 m. Although literature indicates 10 minutes as possible, after initial tests and to avoid long exposure to the IVE, which may increase the chance of negative side effects, it was decided to limit each immersive experiment to two minutes. This decision also supports findings on avoiding memory-based tasks (Abeele *et al.*, 2021). By doing so, we changed our experimental design so that each participant experiences one condition which is now divided into the three shorter experiences, each with a critical eventdefined before.

We opted for using Oculus Meta Quest Pro for its good acceptability and moderate weight (Huygelier *et al.*, 2019). Although initially we aimed at using head movements for directions, we later abandoned it because it would introduce another level of difficulty to our participants and opted for using only the joystick to control the movement (move at constant speed, stop, move right, move left) for its simplicity in use. Participants will perform the experiment seated to avoid fatigue and discomfort.

Gaze and HBR data will be collected throughout the navigation, following previous studies (Nelson *et al.*, 2020). Using the Meta Quest Pro headset, which supports eye-tracking and real-time gaze recording, the Unity environment is configured to collect data continuously during the VR experience. To ensure optimal performance and a smooth VR experience, all data is streamed directly to a connected laptop. Although the system tracks the entire environment, it prioritises specific elements, such as trees, critical elements (e.g., potholes, bikes), sidewalks, car lanes, and bike lanes. Particular attention will be given to gaze data within a 30-second window: 10 seconds before encountering a critical event, 10 seconds during, and 10 seconds after. Heartbeat data will also be collected in real time, following a similar data collection strategy as the eye-tracking system. For this purpose, we will use the Banda Cardio ANT+/ Bluetooth HRM Belt and the Huawei Band 9, both of which offer continuous heart rate (HR) monitoring with real-time capabilities, tracking HR at near-second intervals regardless of

Fig.03 Part of the street in condition C (with vegetation and with join lanes), where agents can be visible.

activity level. As with eye-tracking, the HR data will be collected continuously in the connected laptop throughout the VR experience, but special focus will be placed on a 30-second window surrounding each obstacle: 10 seconds before, 10 seconds during, and 10 seconds after. All gaze and heartbeat data will be synchronised and organised in a structured data table to support detailed analysis.

Conclusions and future work

As outlined earlier, the Greencity4Aging project seeks to investigate the influence of green street designs on older adults' mobility, social integration, and encounters with ageism. Additionally, it examines how urban environments may affect societal perceptions of ageing, thereby offering an innovative assessment of stereotype-embodiment theory.

By using an experimental design approach with an IVEwe examine the causal impact of different environmental settings on perceived walkability, social integration, and ageism. Using an IVE enables us to simulate both 'green' and 'non-green' settings and test the causal effects of specific street characteristics on both subjective (perceived walkability, social integration, and ageism levels) and objective outcomes (gaze and HBR). IVEs are known to generate a greater sense of presence compared to other forms of visualisation, such as static images (Birenboim *et al.*, 2019). Given the specificity of the experimental design, this paper details each design decision, analyses its impact on older participants, and reviews how similar aspects have been treated in the existing literature. In doing so, it highlights the importance of continuously assessing and refining VR design guidelines through preliminary testing to better align with experimental goals and the needs of the target population.

The next steps of the study involve conducting the experiments with approximately 80 older adults, followed by a comprehensive data analysis phase. Findings from the GreenCity4Aging project are expected to offer valuable insights into the dynamics of how older adults interact with green urban environments, ultimately contributing to more inclusive and age-friendly urban planning practices in the future.

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